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Estimation of Regurgitant Flow Volume Based on Centerline Velocity/Distance Profiles Using Digital Color M-Q Doppler: Application to Orifices of Different Shapes

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Objectives. **In this study we investigated the centerline velocity profile method for flow computation as applied to noncircular, as well as circular, orifices using digital color flow data.**

Background. **Recently it has been suggested that flow volume through an orifice can be estimated more accurately by computing the axial "centerline" flow velocity/distance profile proximal to the orifice.**

Methods. **A total of seven different orifices were mounted in a constant-flow model: four circular orifices, two rectangular orifices with a major/minor axis ratio of 4:1 and 8:1 and an ovoid orifice having a major/minor axis ratio of 2:1. Three different flow rates were examined (1.68, 3.48 and 6.48 liters/min). Digital measurements of flow velocity at discrete positions along the centerline progressing toward the orifice were analyzed to yield complete flow velocity profiles for each orifice at each flow rate.**

Results. **A clear separation of the flow profiles for the three different flow rates was observed independent of orifice size for all of the circular orifices. The velocity/distance acceleration curves showed highly significant correlations using multiplicative regression fits ($y = ax^{-b}$, $r = 0.94$ to 0.99, all $p < 0.0001$). An equation for quantitatively correlating the a and b coefficients from the multiplicative regression fits with flow rates was derived from stepwise regression analysis: Flow rate = 23a + 3.3b − 1.5 ($r = 0.97$, $p < 0.0001$, SEE 0.46 liter/min).**

Conclusions. **In view of the various sizes and shapes encountered clinically for regurgitant orifices, the simplicity of this method for the estimation of the severity of regurgitant lesions might be of importance for clinical applications of this method.**

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The noninvasive evaluation of regurgitant lesions has been undertaken by numerous methods (1–5). However, no single method has gained widespread acceptance. The concept of evaluating the flow convergence region using the assumption of isovelocity surfaces has been proposed as a means of estimating regurgitant flow rate (6–12). The clinical application of the method still remains to be strictly validated, especially for the evaluation of mitral regurgitation, partly because the shapes of the regurgitant orifices are highly variable. Preliminary studies have suggested both underestimation and overestimation. Comparisons have been made to angiography, which is not really quantifiable. The calculations in this method are based on the measurement of a distance from the regurgitant orifice and the corresponding velocity, that is, the aliasing velocity. Recently, it has been proposed that flow volume through an orifice can be estimated by an axial "centerline" flow velocity/distance profile (13). In this modified flow convergence method, the complete proximal velocity profile along the centerline of flow toward the orifice is taken into consideration instead of a single velocity and distance pair as used in the simple flow convergence method. This new modified method based on large numbers of data pairs could potentially be more accurate than the flow convergence isovelocity surface method. In the study describing this method, color M-Q Doppler data were used to develop a nomogram for the estimation of flow volume rates that was applicable regardless of orifice sizes (13). The shapes of the orifices in that study, however, were all circular. Because orifice geometry may be one of the most important factors for the evaluation of flow volume using the flow convergence concepts (8,9,14–16), the aim of the present study was to test the centerline velocity/distance profile method as applied to noncircular as well as circular orifices using digital velocity/distance data derived directly from a color Doppler system.

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Methods

Constant-flow model. A total of seven different orifices were mounted in a constant-flow model: four circular orifices with diameters 2.0, 3.8, 5.5 and 10 mm (orifice areas 0.03,

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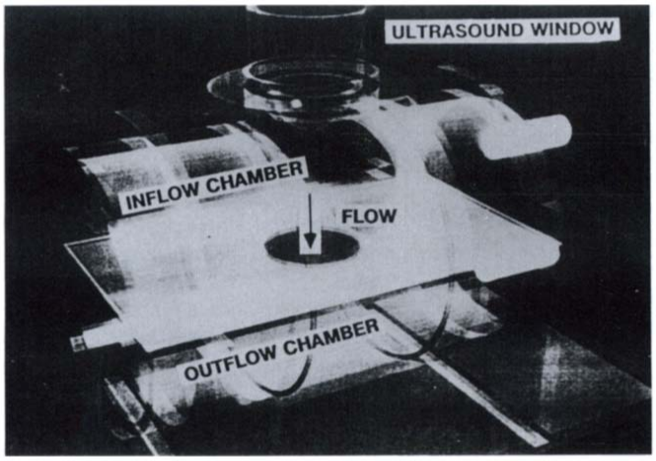
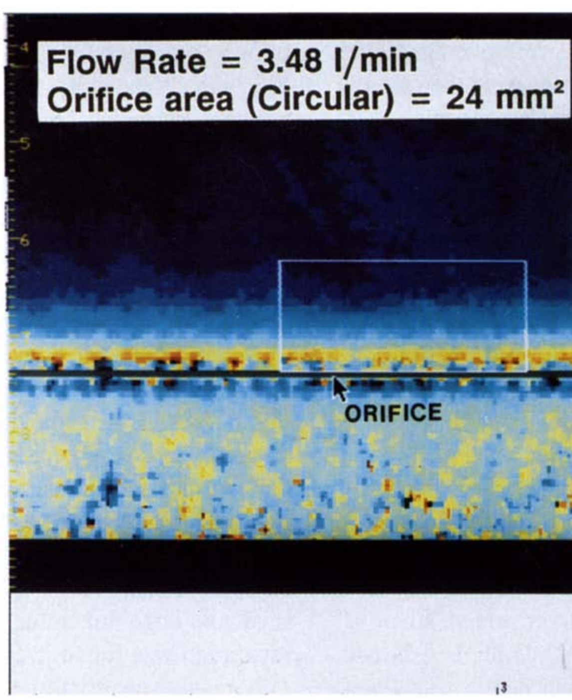


Figure 1. Experimental setup. The flow model apparatus was constructed of transparent acrylic and had an ultrasound window located proximal to the orifice, imaging the flow going away from the orifice.

0.11, 0.24 and 0.79 cm^2), two rectangular orifices with area of 0.24 cm^2 with the ratio of major to minor axis either 4:1 or 8:1 and an ovoid orifice with a orifice area of 0.24 cm^2 with a ratio of major to minor axis of 2:1. Five volume flow rates (1.68, 2.28, 3.48, 5.28 and 6.48 liters/min) were examined. Each flow was driven into the top chamber, through the orifice mounted between the top and bottom chamber, into the bottom chamber and back out to a recirculating pump. A solution of water mixed with 1% by weight cornstarch was used as the fluid medium. Actual flow rate was measured in the model using a rotameter and was cross-checked by measuring flows collected in a graduated cylinder and timed with a stopwatch. The flow model has been described elsewhere (17) (Fig. 1). The design of the system permitted strict control of driving velocity (1.6 to 7.5 m/s) and flow rate. For the small orifices (0.03 and 0.11 cm^2), the two highest flow rates resulted in unphysiologic pressure gradients (maximal flow velocity >8 m/s). Therefore, these data sets were excluded from further analysis. Because the effect of orifice shape on the centerline velocity/distance profiles could be determined at the three flow rates (1.68, 3.48 and 6.48 liters/min), for the other intermediate flow rates of 2.28 and 5.28 liters/min we examined only circular orifices.

Color M-Q mode and data transfer. Color M-Q mode images were recorded with a Vingmed 750 scanner (Vingmed Sound, A/S) interfaced with a Macintosh IIci computer. A 5-MHz transducer was used to record the velocities along the axial centerline through the regurgitant orifices as delineated by two-dimensional imaging and two-dimensional color flow-mapping images. The color M-Q mode line was aligned with the direction of flow through the orifice and perpendicular to the orifice plane. For asymmetric orifices the scans were oriented along the major axis. This system is equipped with a digital output port that allows transfer of the Doppler velocities in their original digital format from the digital scan converter directly into the computer without previous conversion of the signals into analog color-coded format. All flow data in an area of interest marked by the square, as shown in Figure 2, were analyzed. The system allows digital measurements of flow velocity at discrete positions along the centerline for flow proceeding toward the orifice with a distance increment of 0.38 mm and a time increment of 0.005 s (Fig. 2). More than 100 velocity/distance data points for each centerline flow set were analyzed using the computer. Flow velocity was plotted against distance from the orifice, giving complete flow velocity



	A	B	C
9	-0.107	-0.107	-0.107
10	-0.133	-0.107	-0.133
11	-0.133	-0.133	-0.133
12	-0.133	-0.133	-0.133
13	-0.133	-0.133	-0.133
14	-0.133	-0.133	-0.133
15	-0.133	-0.133	-0.133
16	-0.133	-0.16	-0.133
17	-0.16	-0.16	-0.133
18	-0.16	-0.16	-0.133
19	-0.16	-0.16	-0.187
20	-0.187	-0.187	-0.187
21	-0.213	-0.213	-0.187
22	-0.24	-0.24	-0.213
23	-0.267	-0.24	-0.213
24	-0.293	-0.267	-0.267
25	-0.32	-0.293	-0.293
26	-0.32	-0.32	-0.32
27	-0.347	-0.347	-0.347
28	-0.4	-0.4	-0.373
29	-0.427	-0.427	-0.453
30	0.48	-0.453	0.48
31	0.373	0.373	0.4
32	0.293	0.267	0.267
33	0.16	0.213	0.293
34	0.24	0.48	-0.293
35	-0.373	-0.373	-0.373
36	-0.4	-0.453	-0.453

Figure 2. An example of a color M-Q mode recording and digital data transfer. All flow data in the **square** are transferred in their digital format. The **numbers on the right** are sequential samples 0.005 s apart in time, 0.038 cm in space, showing velocities (m/s). Velocity (**blue**) tone increases and progresses through the first alias on **lines 30 and 31**, when the velocities became positive (**yellow-red**).

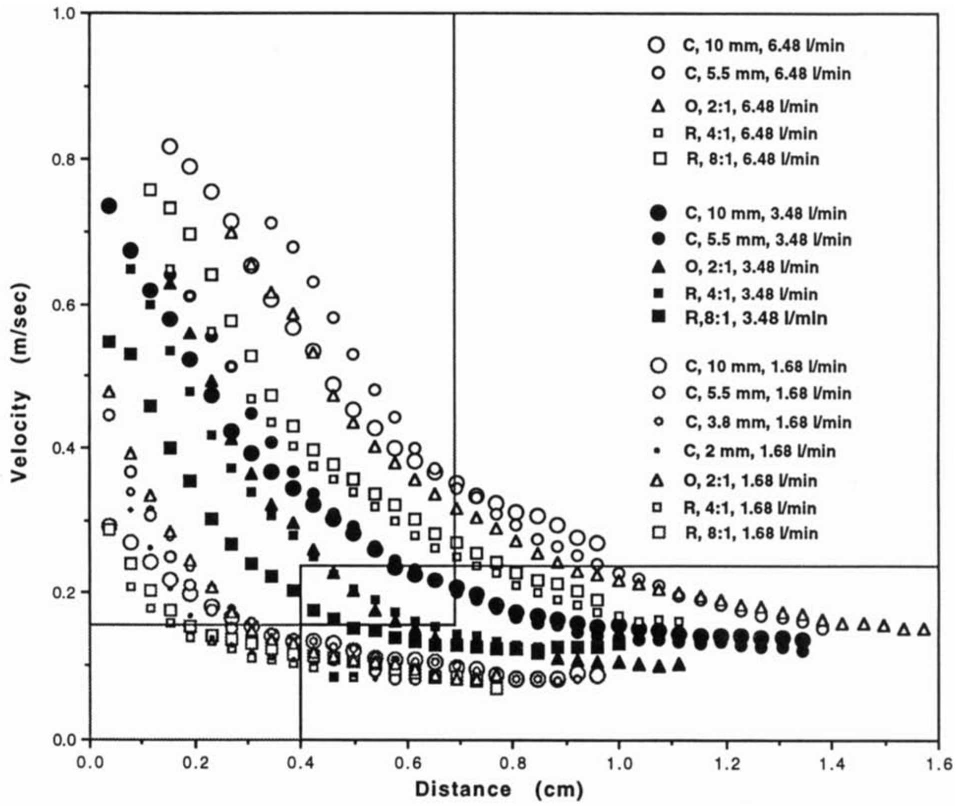


Figure 3. Centerline velocity plot for all orifices with three flow volume rates (1.68, 3.48 and 6.48 liters/min). Cutoff lines of 0.15 and 0.25 m/s and 0.4 and 0.7 cm were chosen for separation of the flow rates. All of the centerline profiles of flow rate of 1.68 liters/min were located in the lower left rectangular domain, 3.48 liters/min in the middle rectangular domain and 6.48 liters/min in the upper right rectangular domain. Thus, three different flow rates were separated using this method. C = circle; O = ovoid (major/minor axis ratio 2:1); R = rectangular (major/minor axis ratio 4:1 or 8:1).

profiles for all orifices and all flow rates investigated. Aliasing was unwrapped, and plots of velocity versus distance were used as the primary data for comparison to flow rate and geometry.

Statistical analysis. To test the hypothesis that the positioning of the centerline velocity/distance profiles for each flow rate was independent of orifice size and shape, all of the data points were resampled, and a linear model was fitted to each of these samples using only the flow rate as a factor. The predicted values at each distance were averaged, and their standard errors were computed. These were then plotted to give 95% confidence bands for the sampled curves.

Interobserver variability. To evaluate the effect of observer variability on the axial centerline velocity/distance profiles of flow convergence, 10 randomly selected flow conditions were analyzed at different times with the same computer by two independent observers, each without knowledge of the results obtained by others or of actual flow data. Both positions of the centerline velocity/distance profiles of flow rates of 1.68, 3.48 and 6.48 liters/min and the a and b coefficients derived from the multiplicative curve fits determined by these observers were compared.

Results

Influence of orifice area. A clear separation of the three different flow volume rates was observed independent of orifice size for all the circular orifices (0.03, 0.11, 0.24 and 0.79 cm^2), as shown in Figure 3. For all flow rates, a tendency for leftward shift of velocity/distance acceleration profiles was observed for the largest orifice compared with the smallest orifice, especially at radii close to the orifice.

Influence of orifice shape. As shown in Figure 3, different positioning of the flow velocity/distance profiles, especially at distances close to the orifice, was noted for the four different orifices investigated, all of which had the same cross-sectional area (0.24 cm^2) but with different geometry. The smallest differences were observed for the ovoid-shaped orifice compared with the circular one. The elongation of the orifice tended to result in a shift of the flow profile leftward, especially close to the orifice. For flow rates of 3.48 and 6.48 liters/min, the best separation between the different flow profiles was observed ~0.4 to 0.5 cm from the orifice, which was nearly the distance of one diameter for the circular orifice. Further from the orifice, the velocity/distance profiles were more similar.

Influence of flow volume rate and orifice geometry. Shown in Figure 3 are the flow velocity/distance profiles for all orifices and flow rates. Close to the orifice, a wide separation of flow profiles was found. At >0.8 cm from the orifice, the flow profiles converged. Because of the leftward shift of the flow profiles for the elongated orifices, a spectrum of separated velocity/distance profiles could be seen for the small (1.68 liters/min), medium (3.48 liters/min) and high flow rates (6.48 liters/min). However, when the profiles for all of the small and large flow rates were analyzed separately, a clear separation was found irrespective of orifice size and shape. This result was confirmed by the 95% confidence bands,

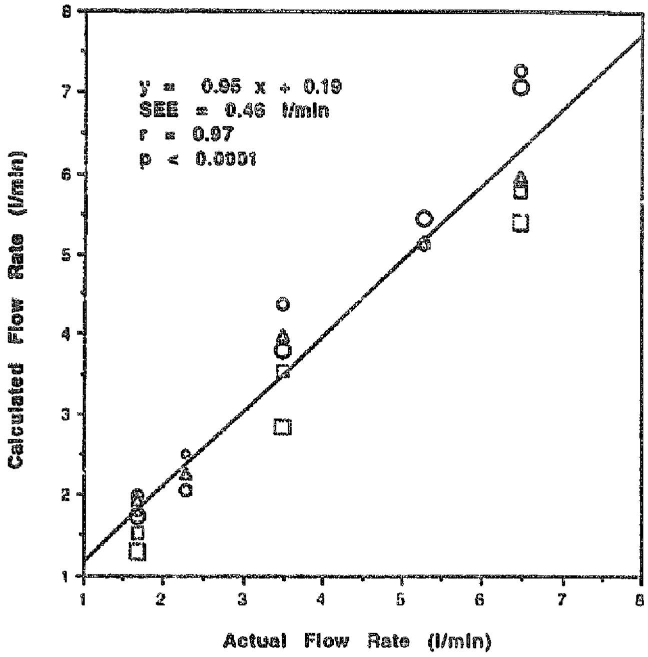


Figure 4. Regression analysis between calculated flow rates using the equation Flow rate = 23a + 3.3b − 1.5, derived from the stepwise regression analysis (see text) and actual flow rate. Symbols as in Figure 3.

which showed no overlap between the three flow rates at the distance from 0.35 cm to 0.9 cm, and by the finding that the results were independent of orifice geometry. A velocity <15 cm/s recorded 4 mm from the orifice indicated a small flow, whereas a velocity >25 cm/s recorded 7 mm from the orifice indicated a large flow. All of the centerline data for the moderate flow rate of 3.48 liters/min fell in a central domain, as shown by the central rectangle in Figure 3.

Quantitative analysis of flow rate using the best curve fits. All of the velocity/distance acceleration curves showed organized acceleration fields with highly significant correlations using multiplicative regression fits ($y = ax^{-b}$, $r = 0.94$ to 0.99, all $p < 0.0001$). Coefficient a ranged from 0.06 to 0.28, and coefficient b ranged from 0.45 to 1.16. Both coefficients a and b correlated with flow rates ($r = 0.94$, $p < 0.0001$; $r = 0.62$, $p < 0.05$, respectively). Because coefficients a and b were not related to each other ($r = 0.31$, $p > 0.05$), stepwise regression was used to examine the relation between the flow rate and these coefficients. This analysis developed an equation for quantitatively correlating coefficients a and b from the multiplicative regressive fits with flow rates: Flow rate = 23a + 3.3b − 1.5 ($r = 0.97$, $p < 0.0001$, SEE 0.46 liter/min) (Fig. 4).

Interobserver variability. Processing of the original digital color M-mode tracings performed by two independent observers revealed very similar axial centerline velocity/distance profiles resulting in placement within the same domain for all of the 10 randomly selected conditions (3 were 1.68 liters/min; 4 were 3.48 liters/min; 3 were 6.48 liters/min). As a result, there was excellent interobserver agreement with regard to coefficient a ($r = 0.98$, SEE = 0.04, mean percent difference 2.3%) and coefficient b ($r = 0.95$, SEE 0.03, mean percent difference 3.8%).

Discussion

Our results suggest that the axial centerline method could be a promising, more advanced noninvasive method for the estimation of flow rate through regurgitant orifices with wide applicability over the range of orifice size and geometry that could be encountered clinically.

Our study confirms findings of Giesler and Stauch (13) with regard to circular orifices. They found that the velocity/distance profiles were independent of orifice size but varied with flow volumes such that close to the orifice, the recorded velocities were slightly higher for small orifices than for larger orifices at the same flow rate. However, their nomograms for velocity/distance plots are shifted slightly to the left compared with ours and would yield lower flow rates. This discrepancy might be explained by the difference between their analog and our digital data analysis, which yielded >100 velocities for analysis for each determination without loss of dynamic range. Our velocity/distance profiles were derived from 16 to 30 points of depth, whereas the lines described in the previous study were obtained by a curve-fitting method applied to fewer points for each nomogram. Background noise and color shifts in analog video data could also lead to velocity underestimation.

Influence of orifice shape. The flow convergence method for evaluating flow volumes depends on many factors, such as pressure gradient between the two chambers, orifice size and the assumption of an isovelocity surface geometric model (6–17). Orifice geometry has been shown to affect the shape of the isovelocity surface, resulting in underestimation or overestimation of actual flow volume (8,9,14–16). Utsunomiya et al. (8,9) suggested the applicability of the hemielliptic isovelocity surface model for calculation of flow volume through an asymmetric orifice. Our study confirmed their observation that the elongation of one axis of the orifice results in a reduction of flow velocity at any distance compared with a circular orifice of the same size and that in such situations a simple hemispheric isovelocity assumption is less valid than the hemielliptic model (8,9,16). However, an elliptic solution needs two or three orthogonal views for the measurements of the different radii, which could limit clinical applicability. In contrast, the axial centerline color M-Q mode method needs only a single two-dimensional view to achieve alignment of the M-mode line with the flow and the orifice. Regardless of orifice shape (and size), in our study the centerline method could differentiate between the ranges of flow rates.

The clear separation between the three flow volume rates could be obtained irrespective of orifice shape by use of velocity/distance domains (Fig. 3), whereas data applied for the simple hemispheric isovelocity surface method most often use a single pair of velocity/distance determinations recorded further away from the orifice. As shown in Figure 3, at these distances >8 mm from the orifice, separation between the velocity/distance profiles is not optimal.

Potential application. In previous clinical studies, the axial length or distance from the orifice to the alias of the flow convergence color change has been shown to predict the severity of obstruction in the left ventricular outflow tract in hypertrophic cardiomyopathy (18), severity of obstruction in aortic coarctation (19) and severity of mitral regurgitation (20). However, in those studies, the effect of the size or shape of the orifice on the prediction of severity was not clarified. Application of the same method to valvular regurgitation has yielded varying results, with difficulties related to the geometric assumptions and the ranges of the Nyquist velocities. In addition, the simple flow convergence method using one pair of velocity/distance data from the orifice needs guidelines for the optimal selection of this data pair for flow estimation in the settings of both valvular regurgitation and stenosis (21–23). In contrast, the centerline method using more complete ranges of velocities along the axial centerline for flow toward the orifice can be applied independently of orifice size and geometry despite the slight leftward and downward shifts of velocity profiles for the larger, elongated orifices. Additionally, single erroneous values that do not fit the overall data can be excluded from the curve fit. This domain method does not directly compute flow rates because it makes no geometric assumptions to relate the velocity/distance pairs to flow rates. Nonetheless, our animal studies have shown that a close fit for prediction of actual regurgitant flow rate can be obtained by examining this method to select particular velocities within the discriminative domain and to use the distance at which those velocities are reached as a direct predictor of flow rate (21). In addition, a quantitative equation was derived from the coefficients a and b obtained from each individual centerline velocity/distance multiplicative regression fit to estimate actual flow rates. In our animal model study (21), the domain technique provided separation of mild, moderate and severe regurgitation, and the quantitative analysis using the coefficients a and b derived from the animal centerline velocity/distance multiplicative regression fits also yielded quantitative estimation of the regurgitant flow rate. Taking into account the various sizes and shapes of the actual regurgitant orifices, this method for the estimation of the severity of regurgitant lesions might be of significant importance for clinical applications compared with the flow convergence isovelocity surface method.

Limitation. One problem with color M-mode methods is that orifice localization is a critical factor for the positioning of the velocity profile relative to the orifice. In the present steady-flow model, this was not a problem. In our in vivo study (21), we encountered difficulty locating and following the position of the regurgitant orifice during recording the color M mode in some circumstances (circa 20%), even though the translational movement of the heart was eliminated by positioning the transducer epicardially. In clinical situations, therefore, great care is needed to correctly identify and track the orifice position. Motion of the orifice is a problem unless the M-mode cursor is adjusted during the cardiac cycle to track the orifice. Clinical studies have, however, shown that in many types of mitral regurgitation, the flow acceleration zone can be tracked by color M mode (22). Once the organized centerline velocity/distance profiles are obtained clinically, however, it should be possible to predict the severity of the regurgitation and to quantify the flow rate using this method.

Conclusions. The centerline velocity/distance profile analysis is a nongeometric digital method that could potentially provide information with regard to flow rate through regurgitant lesions irrespective of orifice size and geometry. Additionally, the digital stream of color M-mode derived data pairs could potentially be computer automated, making this method more widely applicable and reproducible than previously reported methods.

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